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Middle Cambrian high magnetic reversal frequency (Kulumbe river section, northwestern Siberia) and reversal behaviour during the Early Palaeozoic

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Abstract

We present a magnetostratigraphic study of Middle Cambrian sediments along the Kulumbe river (northwestern Siberia). The deposits are ~850 m thick and lie within the Mayan stage as constrained by trilobite fossils. Palaeomagnetic analyses reveal two magnetic components. The first component, parallel to the direction of the present day field at the site, is isolated in the low to middle temperature range. A high temperature component (HTC) is then isolated up to 580 or 680°C, carried either by magnetite and/or by hematite. The HTC defines a sequence of 28 magnetic polarity intervals, some of them being defined by only one sample. Considering that the studied section has a duration of ~5 Myr, we propose that the magnetic reversal frequency was high (~4–6 reversals per Myr) during part of the Middle Cambrian, among the highest values known within the Phanerozoic. The reversal frequency may have been roughly similar during the Lower Cambrian. We further suggest a drastic decrease of the magnetic reversal frequency between the Lower–Middle Cambrian and the end of the Tremadoc (Ordovician) when a superchron probably occurred. However, this behaviour is still challenged by other scenarios which depend on the chosen Early Palaeozoic time scale and on the reliability of some magnetostratigraphic data.

Keywords: Magnetostratigraphy; Magnetic reversal frequency; Early Paleozoic; Siberia

1. Introduction

The existence of magnetic polarity reversals is probably as old as the generation of the geomagnetic field itself. Gubbins [1] recently speculated that geomagnetic reversals were much more frequent, approximately by a factor of 10, before the growth of the solid inner core than after. The inner core may indeed stabilise the magnetic field generated in the liquid outer core (e.g. [2,3]). Age estimates for the inner core strongly depend on which cooling model is considered for the Earth, with one of the latest possibilities being younger than 1.7 billion years [4]. No magnetostratigraphic record showing a succession of several magnetic reversals is presently known for periods older than 2 Ga. Between 2 and 1 Ga, magnetostratigraphic results are very rare (e.g. [5,6]), partly because of the difficulty of finding non-re-

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magnetised Precambrian sedimentary sections. Gallet et al. [7] recently reported relatively numerous geomagnetic reversals in several sedimentary sections deposited ~1050–1100 Myr ago from the northwestern and the southeastern parts of the Siberian platform. These results may indicate a moderate to high magnetic reversal frequency during a part of the late Mesoproterozoic, but a frequency value cannot be estimated because of the absence of precise dating constraints. The oldest time-constrained magnetic reversal frequency lies within the Lower Cambrian. There, Kirschvink and Rozanov [8] found many polarity reversals from biostratigraphically well-dated Tommotian, Atdabanian and Botomian sedimentary sections along the Lena river (Siberia). However, the interpretation of these results is controversial because the palaeomagnetic pole obtained by Kirschvink and Rozanov [8] is significantly different to other Cambrian poles from the Siberian craton and because a predominant reversed polarity is most often observed during this period (e.g. [9,10]). On the other hand, magnetostratigraphic data from Morocco and China further support the occurrence of several, perhaps numerous, magnetic reversals during the Lower Cambrian [11]. A strong polarity bias is much more evident during the Ordovician (in the Arenig and the Llanvirn), which is interpreted by Algeo [12], Gallet and Pavlov [13] and Pavlov and Gallet [14] as a superchron lasting approximately 15–20 Myr. If true, it would suggest the persistence of a ~150 Myr-long time constant over the whole Phanerozoic [13,15]. However, this hypothetical superchron is in need of further confirmation and it must be integrated in the general evolution of the magnetic reversal frequency during the Early Palaeozoic. For this reason, we returned to the Kulumbe river area (northwestern Siberia) where Upper Cambrian, Lower and Middle Ordovician (Tremadoc and Llanvirn stages, respectively) magnetostratigraphic results were already obtained by Pavlov and Gallet [14]. We present in this study the magnetostratigraphy of the very thick Middle Cambrian part of the Kulumbe section.

2. Description of the Middle Cambrian Kulumbe river section

The studied section is located in the lower stream valley of the Kulumbe river, about 100 km to the east of the Yenisey river, in the northwest of the Siberian platform (Fig. 1; see also Fig. 1 in Pavlov and Gallet [14]). Tectonically, this area lies on the margin of the Siberian craton, within the bounds of the Khantayka–Rybnaya uplift of the Turukhansk–Norilsk dislocation zone (e.g. [16]). The Middle Cambrian deposits crop out along both sides of the Kulumbe river over a distance of 6–7 km (latitude: 68.0°N, longitude: 88.4°E). This sedimentary sequence is ~850 m thick and consists of grey, greenish grey and reddish limestones, argillaceous limestones and marlstones that dip gently (15–20°) to the east–southeast. The upper 630 m of the section belongs to the Labaznaya Formation, while the lower part of the sequence belongs to the upper part of the Ust–Brus Formation (e.g.

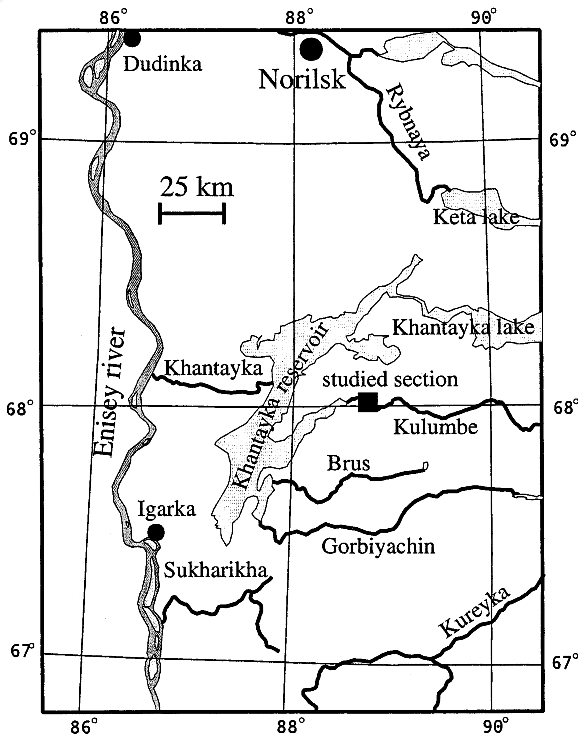

Fig. 1. Locality map of the studied Kulumbe river section.

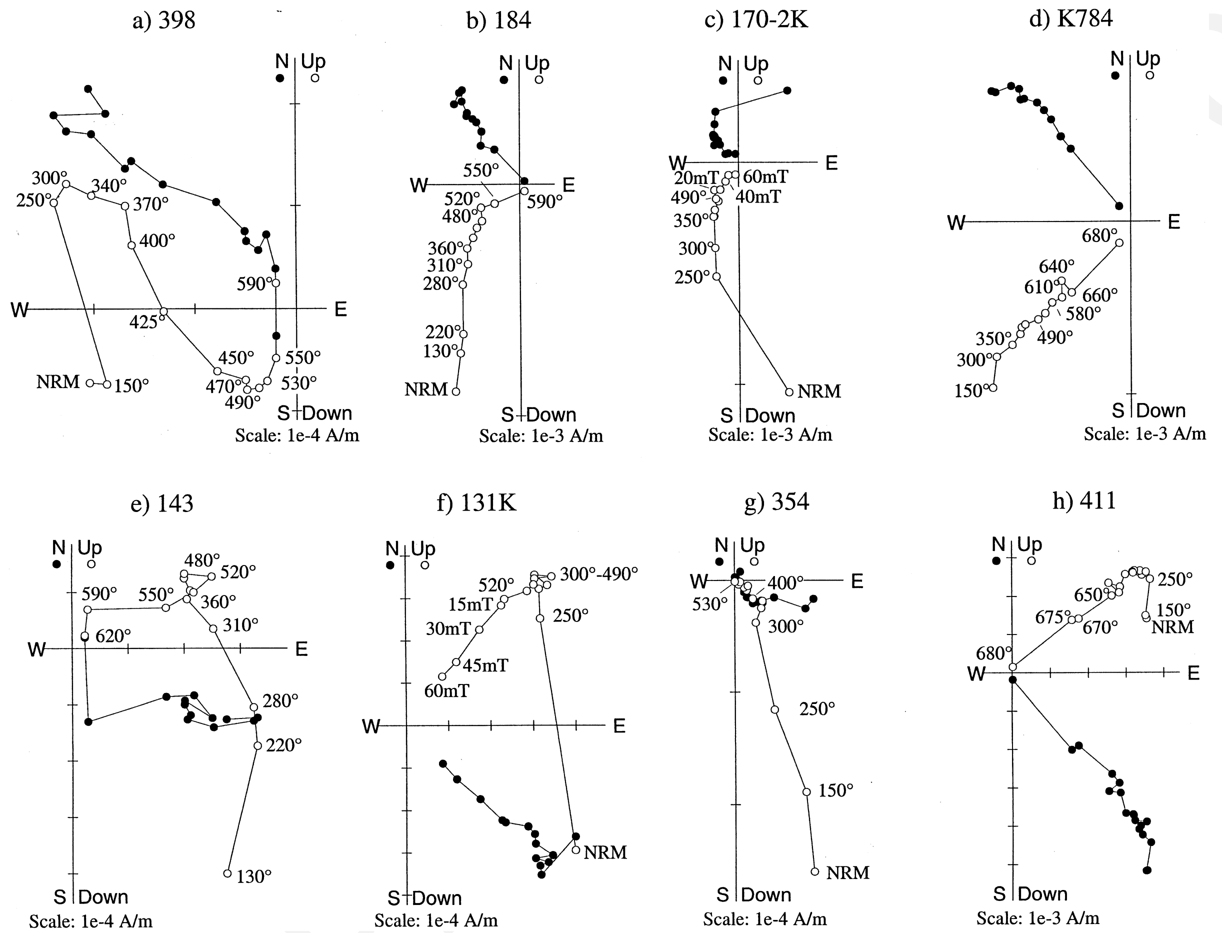

Fig. 2. Orthogonal vector diagrams obtained by thermal and hybrid thermal-AF demagnetisation of samples from the Kulumbe river section. The closed (open) symbols refer to the horizontal (vertical) plane. All the diagrams are shown after bedding correction.

[17–20]). Both formations have very similar lithologies, although reddish colours are more typical of the Ust–Brus Formation. Magmatic intrusions (sills and dykes) are present at two restricted stratigraphic intervals within the first half of the Labaznaya Formation.

The thoroughly studied biostratigraphic zonation of the Middle Cambrian section is essentially based on a rich fauna of trilobites (e.g. [17,18,20,21]). Two trilobite zones are distinguished within the section. The upper *Lejopyge laevigata*/*Aldanaspis truncata* zone extends over the top 340–350 m of the Labaznaya Formation, and is characterised by the following trilobite species: *Maiaspis mirabilis N. Tchern*, *Bonneterrina sachaica Ros.*, *Nganasanella nganasanennsis Ros.*, *Kontrastina samodiica Ros.*, *Buitella olenekensis Laz.* and *Bolaspidina insignis N. Tchern*. The Middle–Upper Cambrian boundary, which is marked by an abrupt change of trilobite assemblages, is traced to the top of the Labaznaya Formation, and at the base of the overlying Orakta Formation [19,20]. The lower part of the Labaznaya Formation and the upper part of the Ust–Brus Formation exposed in the Kulumbe section lie within the *Anomocariodes limbaraeformis* zone, characterised in particular by the trilobite species *Agraulos acuminatus Ang.*, *Phalacroma glandiforme Ang.*, *Aldanaspis venusta Laz.*, *Oidalagnos-*

tus trispinifer Wgard., *Anomocarina splendens Lerm.* and *Anomocarioides* sp.

The two trilobite zones found in Kulumbe define the Mayan stage. We note that in Siberia, the Middle Cambrian is composed, from bottom to top, of the Amgan and the Mayan stages. Moreover, the Mayan stage is defined by three trilobite zones in the Siberian biostratigraphic time scale, the oldest of which (the *Anopolenus henrici/Corynexochus perforatus* zone [22]) is not exposed in the Kulumbe river valley. The Amgan stage is also defined by three trilobite zones [22]), and despite its thickness, our section therefore contains only two of the six Middle Cambrian Siberian trilobite zones.

3. Palaeomagnetic results

Approximately 450 oriented hand-samples were collected in 1998 with a stratigraphic sampling interval of 1–2.5 m. Their remanent magnetisations were analysed in the palaeomagnetic laboratory at Institut de Physique du Globe de Paris with a CTF three-axis cryogenic magnetometer housed in a shielded room.

Thermal demagnetisation, performed with a laboratory-built furnace, generally reveals two magnetic components. The first (low temperature component, LTC) is often isolated over a wide temperature range from 130°C to about 500°C (Fig. 2). The LTC directions are parallel to the present day field direction at the site, indicating that this component has likely a recent viscous or chemical origin (Table 1; Fig. 3a). A high temperature component (HTC), which trends toward the origin on the orthogonal vector diagrams, is isolated at higher temperatures, up to 580 or 680°C. However, in many samples, the demagnetisation paths become scattered at high temperatures, preventing a clear estimate of the HTC directions (Fig. 2e). To avoid this effect, we performed for some samples hybrid thermal-alternating field (AF) demagnetisations. Our treatment indicates that the HTC component is carried by magnetite or hematite (Fig. 2a,b,c,e,f,g and d,h, respectively). In some cases, AF demagnetisation removes only a part of the HTC component, which may indicate that it is locally carried both by magnetite and hematite. To characterise better the magnetic mineralogy, we have thermally demagnetised a composite (fields of 1.2 and 0.3 T applied in two perpendicular directions [22]) isothermal remanent magnetisation (IRM). The examples shown in Fig. 4 confirm that the magnetisation is either carried by magnetite (Fig. 4a), hematite (Fig. 4b) or by a mixture of magnetite and hematite (Fig. 4c).

In several samples collected close to magmatic intrusions, a third magnetic component is removed in the middle temperature range, between the LTC and HTC components (Fig. 2a). In a few cases, this component persists until the samples are completely demagnetised. This component has a steep upward inclination and is directed toward the northwest (Fig. 3b), which is a direction similar to the one we previously found from other intrusions located in the Upper Cambrian and Ordocician parts of the Kulumbe section [14]. These intrusions are related to the emplacement of the Siberian traps, and we therefore consider that this magnetic component was acquired at the Permo–Triassic boundary (Table 1; see also [13]).

The HTC component possesses dual magnetic polarities (Fig. 3c). Some directions are clearly biased by the LTC component, and this is attested by the fact that the mean normal and reversed polarity directions are not antiparallel (Fig. 5, left; Table 1 [23]). This bias likely results from the large overlap between the demagnetisation spectra of the LTC and HTC components, together with the scatter observed at high temperatures in the demagnetisation paths. In Fig. 3d, we have tentatively selected only the HTC directions which are obviously less contaminated by the LTC component. The mean normal and reversed directions of this population are still not antipodal, but the angular difference between these two directions is much less than before (Fig. 5, right; Table 1). This indicates that our selection is not fully satisfactory but we note that the two general mean directions computed before and after the selection are almost identical (MEAN 1 and MEAN 2, Table 1). We therefore consider that the averaging of the normal and reversed polarity directions al-

Table 1
Directions of the LTC and HTC obtained from the Middle Cambrian Kulumbe river section

	N	Geographic coordinates				Stratigraphic coordinates			
		D (°)	I (°)	K	α_{95} (°)	D (°)	I (°)	K	α_{95} (°)
Remagnetisation components:									
LTC component	426	342.7	78.5	25.9	1.4	81.0	81.0	24.1	1.4
Trap remagnetisation	9	315.0	−74.1	127.9	4.6	310.4	−64.6	114.2	4.8
HTC component:									
Normal polarity	53	143.6	−19.7	19.1	4.6	146.9	−35.6	20.3	4.5
Reversed polarity	226	319.2	32.7	17.6	2.3	322.8	48.1	26.0	1.9
MEAN 1	279	140.1	−30.2	16.7	2.1	143.7	−45.8	22.7	1.8
HTC component after selection:									
Normal polarity	29	141.8	−22.8	29.8	5.0	144.8	−38.0	31.8	4.8
Reversed polarity	99	319.5	31.1	21.9	3.1	321.9	45.4	30.8	2.6
MEAN 2	128	140.0	−29.2	22.4	2.7	142.6	−43.7	29.8	2.3

lows a good estimate of the geomagnetic direction prevailing at the time of the sediment deposition.

In the absence of a fold test, the arguments for the early origin of the HTC component arise from the fact that (1) different magnetic minerals carry the same HTC palaeomagnetic direction and (2)

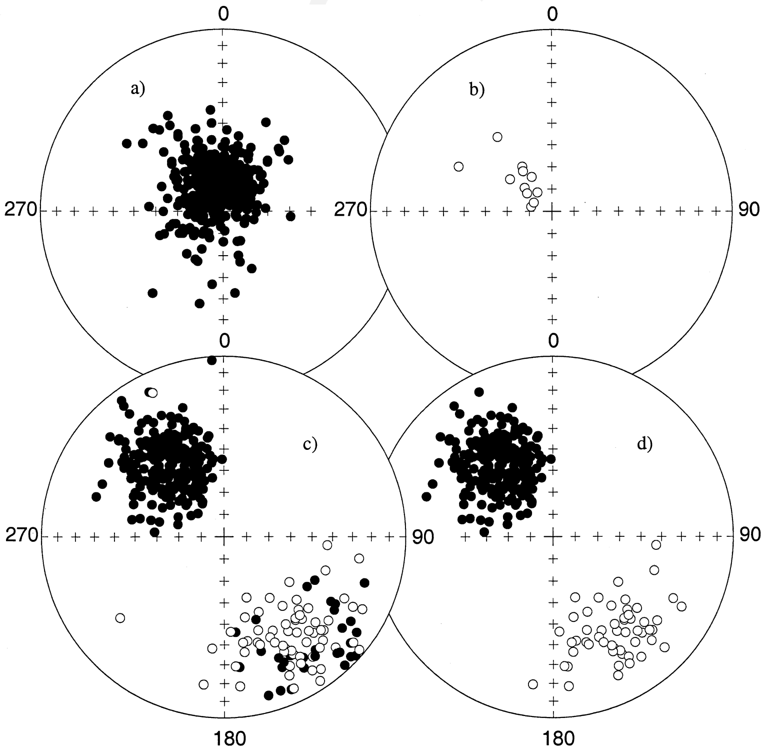

Fig. 3. Equal-area projection of palaeomagnetic directions isolated within the Middle Cambrian part of the Kulumbe section. Closed (open) symbols refer to directions in the lower (upper) hemisphere. (a) Directions obtained before bedding correction for the LTC. (b) Directions of reversed polarity observed in samples close to trap intrusions (before tilt correction). (c) Directions of the HTC isolated after bedding correction. (d) Selection of apparently unbiased directions of the HTC.

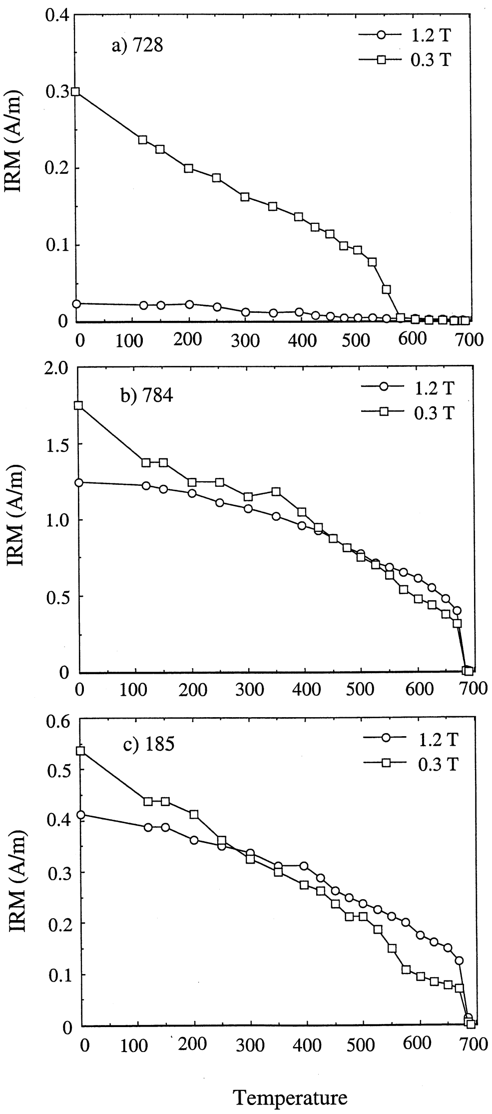

Fig. 4. Thermal demagnetisation of a two-axial differential IRM (0.3 and 1.2 T). The magnetisation is carried either by magnetite (a), hematite (b) or both by magnetite and hematite (c).

the HTC direction is similar (but statistically distinct) to younger palaeomagnetic directions previously obtained from the Kulumbe and the Moyero river sections [13,14]. The Middle Cambrian mean direction is upward (downward) to the southeast (northwest), and assuming that the Siberian craton was located in the southern hemisphere, it indicates that the present Siberian northern shorelines were facing south at this time (e.g. [13,14,24–26]). Another important characteristic, which strongly argues for the primary origin of the HTC component, is that the Middle Cambrian direction is in direct continuity with the Middle Ordovician to Upper Cambrian Apparent Polar Wander Path of Siberia constructed from the Kulumbe and Moyero magnetostratigraphic results (Fig. 6). Moreover, the new data from the Kulumbe section are in relatively good agreement with the Middle Cambrian (mainly of Amgan age) palaeomagnetic pole obtained from the Siberian Olenek section (Fig. 6 [10,27]).

Fig. 7 shows the declination and inclination records versus depth. The closed symbols indicate the directions which, we believe, are biased by the LTC component. The LTC contamination which has a high inclination principally affects the inclinations of the HTC component, and the HTC declinations therefore define more distinctly the magnetic polarities. We obtain a sequence of 28 magnetic polarity intervals, four of them being defined by a single sample (Fig. 7). Moreover, three magnetic intervals are only defined by biased directions (respectively by one, one and two samples). There are two breaks in the middle part of the magnetostratigraphic sequence due to remagnetisation linked to the emplacement of the traps. The upper part of the section exhibits predominantly reversed polarity, whereas polarity reversals are frequent in the lower half of the sequence.

4. Discussion

The new section sampled along the Kulumbe river shows numerous geomagnetic polarity reversals. We note here that Khramov et al. [28] previously reported the occurrence of several magnetic polarity reversals from Middle Cambrian deposits exposed along the upper stream of the Olenek river. Together with other data from the literature, these results can be used to constrain the magnetic reversal behaviour during the Cambrian. This is possible because some geochronological data are presently available for this period, although the time frame for the different Cambri-

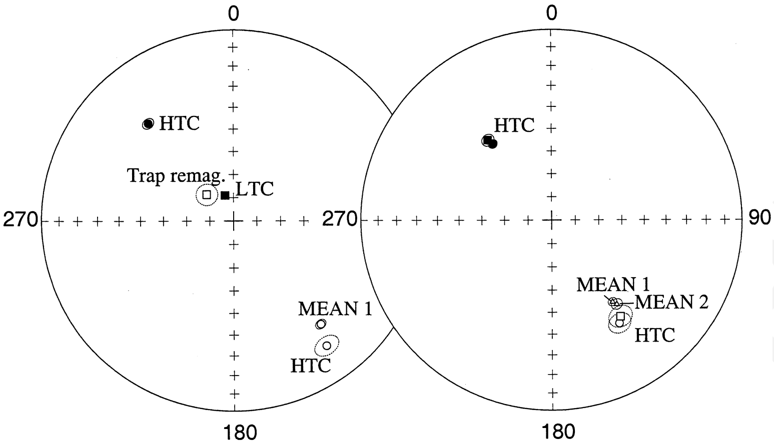

Fig. 5. Mean palaeomagnetic directions obtained in Kulumbe. Same convention as in Fig. 3. Left: Mean directions of the different components obtained before bedding correction. Right: Mean normal and reversed polarity directions in stratigraphic coordinate system obtained for the HTC before (closed and open circles) and after (closed and open squares) a selection of the data. The respective general mean directions are indicated by triangles (MEAN 1 and MEAN 2; Table 1).

an subdivisions is still not yet established without uncertainty.

From studies dealing with the Cambrian time scale (e.g. [29–34] and references therein) it appears that two main characteristics are quite well-established: (1) the duration of the Lower Cambrian (∼25 Myr) is about one half of the duration of the entire Cambrian and (2) the duration of the Middle Cambrian is likely short compared to the Lower Cambrian.

The duration of the Middle Cambrian was considered between ∼5 and ∼20 Myr. The Middle–Upper Cambrian boundary was recently proposed to lie between 498 Ma [33] and 505 Ma [31,32,35], while the age of the Lower–Middle Cambrian boundary ranges from 510 Ma ([36], considered by Meert [34]) to 518 Ma ([31], used by Kirschvink et al. [37]). As discussed by Jago and Haines [35], most of these uncertainties depend on the measured ages of the standards used for radiometric datings. However, following Tucker and McKerrow [31] and Jago and Haines [35], 505 Ma is most probable for the Middle–Upper Cambrian boundary. Age constraints for the base of the Middle Cambrian are much more uncertain. A duration as short as 5 Myr for the Middle Cambrian (with a Lower–Middle Cambrian boundary at 510 Ma) would be very brief with respect to the number of trilobite zones which occurred during this period (e.g. [35,38]). For this reason, we will consider here a duration of ∼13 Myr for the entire Middle Cambrian, which takes into account the oldest (but still reasonable) age suggested for the Lower–Middle Cambrian boundary (518 Ma [31]). This duration is likely a maximum estimate and the derived magnetic reversal frequency will thus be a minimum estimate.

There are no data to constrain the relative du-

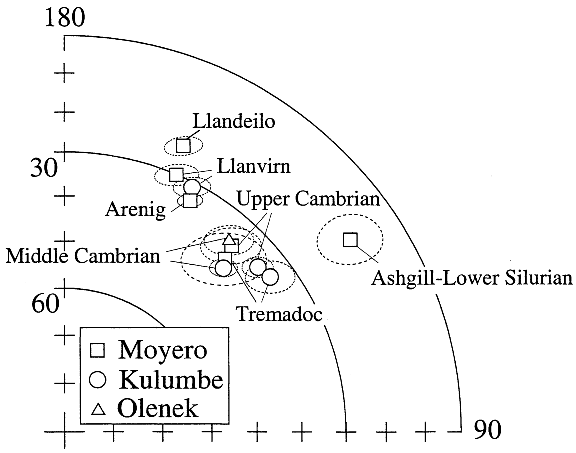

Fig. 6. Equal-area projection of the Lower Silurian to Middle Cambrian. Palaeomagnetic poles obtained from the Moyero (squares; [13]), Kulumbe (circles; [14]) and Olenek (triangle; [10]) river sections.

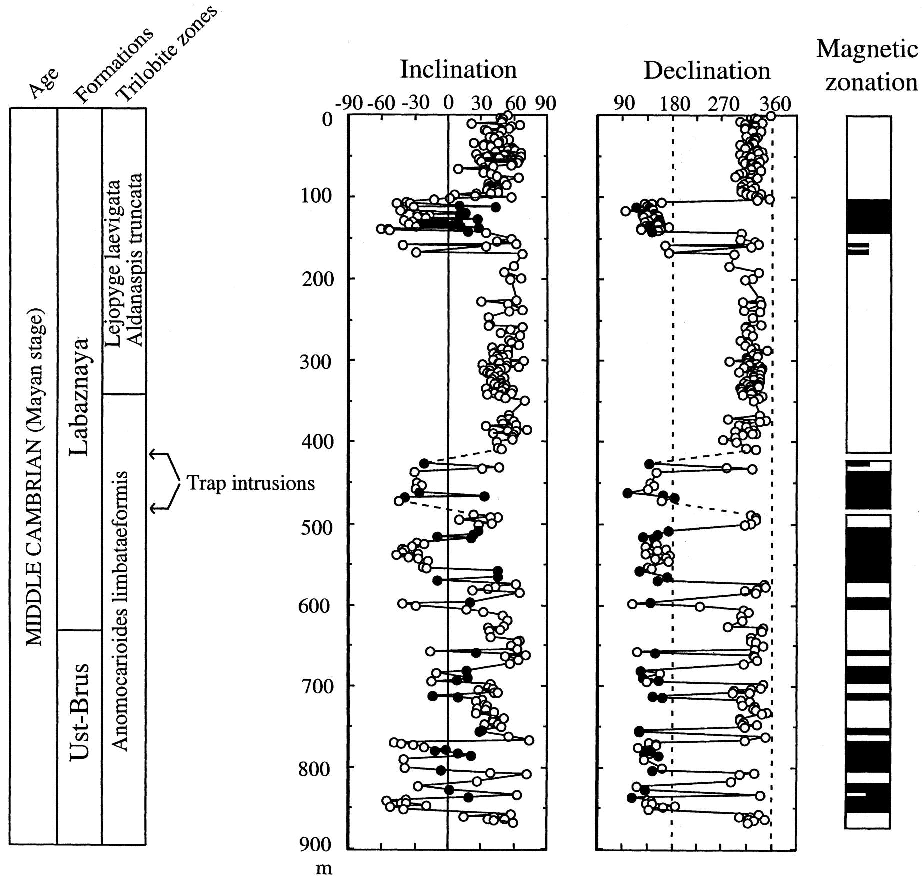

Fig. 7. Magnetostratigraphy of the Middle Cambrian part of the Kulumbe river section. Magnetic intervals defined by only one sample are indicated by half bars. Directions clearly biased by remagnetisation are shown by closed circles.

rations of the Amgan and the Mayan stages defining the Middle Cambrian in Siberia. The only possibility is to do a very rough approximation which consists of assuming an equal duration for the Middle Cambrian trilobite zones. This approximation is far from satisfactory because it is untested. However, it yields a first order estimate of ~5 Myr for the duration of our section which encompasses two of the six trilobite zones. In Kulumbe, 28 magnetic polarity reversals are observed, but 20 if only intervals defined by several samples are retained. The latter values constrain the magnetic reversal frequency to be between four and six reversals per Myr during approximately the upper one third of the Middle Cambrian. This estimate can be tentatively tested by considering the correlation already proposed between the Australian and Siberian Middle Cambrian biozonations. According to Shergold et al. [37] and Jago and Haines [35], the *L. laevigata* and *A. limbataeformis* zones from the Kulumbe section should correspond to a succession of seven trilobite zones from Australia (from the *C. quasivespa* to the *G. narthorstic* zones). Further assuming the average time span of ~0.55 Myr for the Australian Middle Cambrian (and Upper Cambrian) trilobite zones proposed by Jago and Haines [35], the sampled Kulumbe section would have a duration of ~4 Myr, roughly similar to the duration we previously estimated. In both cases, the magnetic reversal frequency that we derived from the Kulumbe data is among the highest observed during the Phanerozoic, comparable to those prevailing during the Miocene and the Middle–Upper Jurassic.

As mentioned above, the magnetostratigraphy of the Lower Cambrian is presently obscured by the problem of the reliability of the data obtained by Kirschvink and Rozanov [8] from the Lena river. If their results give a good picture of the reversal polarity sequence at the base of the Palaeozoic, then it is of interest to compare the reversal behaviour during the Lower Cambrian with that of the Middle Cambrian. The computation of magnetic reversal frequencies during the Lower Cambrian strongly relies on the relative durations of the Tommotian and Atdabanian stages. This is also of major importance for understanding the biological diversification within the Lower Cambrian (e.g. [37,39]). There are several options according to published Cambrian time scales. Tucker and McKerrow [31] proposed that both stages would have a similar duration of $\sim$5 Myr. Data obtained by Kirschvink and Rozanov [8] would then indicate high reversal frequencies of $\sim$4 reversals per Myr for the Tommotian and $\sim$6–7 reversals per Myr for the Atdabanian, very comparable to the value that we propose during the Middle Cambrian. However, zircon U–Pb ages obtained close to the base of the Tommotian [39] and to the Tommotian–Atdabanian boundary [40] suggest that the duration of the Tommotian was perhaps longer by a factor of two. In this case, reversal frequencies would be notably different between the Tommotian, characterised by a moderate frequency, and the Atdabanian. A more extreme possibility supported by Meert [34] is that the duration of the Tommotian is about 15 Myr, while the Atdabanian would be much shorter ($\sim$2–3 Myr). These durations imply unusually rapid changes in magnetic reversal frequency, with a very high value ($>$10 reversals per Myr) during the Atdabanian and a low value during the Tommotian ($\sim$1.5 reversal per Myr). Such a rapid behaviour has no equivalent during the last 160 Myr, so a conservative attitude is to favour one of the two first options.

Computing Upper Cambrian and lowermost Ordovician (Tremadoc) magnetic reversal frequencies is complicated by uncertainties in correlating Siberian biostratigraphy with the standard geologic time scale based on graptolite biozonation from British sections (e.g. [21,41]). This may be partly the reason for the relatively poor correlation between magnetostratigraphic results from Kulumbe [14] and from the Dayancha and Black Mountain sections [42,43]. However, considering a duration of $\sim$20 Myr between the Middle–Upper Cambrian boundary (505 Ma [31,35]) and the Tremadoc–Arenig boundary (485 Ma [31]), the available magnetostratigraphic data taken globally seem to indicate a moderate magnetic reversal frequency, most probably lower than during the Middle Cambrian.

At this stage of our knowledge, we propose a drastic decrease in magnetic reversal frequency between the Lower (?)–Middle Cambrian and the end of the Tremadoc stage when a superchron probably occurred [12,13]. This behaviour would be similar to the one prevailing during the Lower Cretaceous, before the Cretaceous Long Normal superchron. However, we recognise that it is presently challenged by other scenarios which depend on the chosen Cambrian time scale and on the reliability of some magnetostratigraphic data. Finally, the new data from Kulumbe clearly do not support the idea that geomagnetic reversals were less frequent during the Lower Palaeozoic than during the last 300 Myr, as is suggested by Figure 1 of Eide and Torsvik [44]. The Palaeozoic magnetostratigraphic database is probably too limited to support such an inference.

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References

[1] D. Gubbins, The distinction between geomagnetic excursions and reversals, Geophys. J. Int. 137 (1999) F1–F3.
[2] R. Hollerbach, C. Jones, Influence of the Earth's inner core on geomagnetic fluctuations and reversals, Nature 365 (1993) 541–543.
[3] S. Gilder, J. Glen, Magnetic properties of hexagonal closed-packed iron deduced from direct observations in a diamond anvil cell, Science 279 (1998) 72–74.
[4] S. Labrosse, J.-P. Poirier, J.-L. Le Mouël, On cooling of the Earth's core, Phys. Earth Planet. Int. 99 (1997) 1–17.
[5] D. Bingham, M. Evans, Precambrian geomagnetic field reversal, Nature 253 (1975) 332–333.
[6] D. Elston, S. Bressler, Paleomagnetic poles and polarity zonation from the Middle Proterozoic Belt supergroup, Montana and Idaho, J. Geophys. Res. 85 (1980) 339–355.
[7] Y. Gallet, V. Pavlov, M. Semikhatov, P. Petrov, Late Mesoproterozic magnetostratigraphic results from Siberia: Paleogeographic implications and magnetic field behaviour, J. Geophys. Res. 105 (2000) 16481–16500.
[8] J. Kirschvink, A. Rozanov, Magnetostratigraphy of Lower Cambrian strata from the Siberian platform: a paleomagnetic pole and a preliminary polarity time-scale, Geol. Mag. 121 (1984) 189–203.
[9] A. Khramov, V. Rodionov, The geomagnetic field during the Palaeozoic time, J. Geomagn. Geoelectr. 32 (sup. III) (1980) 99–115.
[10] S. Pisarevsky, E. Gurevich, A. Khramov, Paleomagnetism of the Lower Cambrian sediments from the Olenek river section (northern Siberia): paleopoles and the problem of the magnetic polarity in the Early Cambrian, Geophys. J. Int. 130 (1997) 746–756.
[11] J. Kirschvink, M. Margaritz, R. Ripperdam, Y. Zhuravlev, A. Rozanov, The Precambrian–Cambrian boundary: magnetostratigraphy and Carbon isotopes resolve correlation problems between Siberia, Morocco, and South China, GSA Today 1–4 (1991) 69–91.
[12] T. Algeo, Geomagnetic polarity bias patterns through the Phanerozoic, J. Geophys. Res. 101 (1996) 2785–2814.
[13] Y. Gallet, V. Pavlov, Magnetostratigraphy of the Moyero river section (north-western Siberia): constraints on geomagnetic reversal frequency during the early Palaeozoic, Geophys. J. Int. 125 (1996) 95–105.
[14] V. Pavlov, Y. Gallet, Upper Cambrian to Middle Ordovician magnetostratigraphy from the Kulumbe river section (northwestern Siberia), Phys. Earth Planet. Int. 108 (1998) 49–59.
[15] Y. Gallet, J. Besse, L. Krystyn, J. Marcoux, H. Théveniaut, Magnetostratigraphy of the Bolücektasi Tepe section (southwestern Turkey): implications for changes in magnetic reversal frequency, Phys. Earth Planet. Int. 73 (1992) 85–108.
[16] N. Malich, Tectonic Development of the Sedimentary Cover of the Siberian Platform, Nedra, Leningrad, 1975, p. 216 (in Russian).
[17] A. Rozova, Biostratigraphy and Description of the Trilobites of Middle and Upper Cambrian of the Siberian Platform, Nauka, Moscow, 1964, p. 146 (in Russian).
[18] V. Datsenko, I. Zhuravleva, N. Lazarenko, Y. Popov, N. Chernychova, Biostratigraphy and Fauna of Cambrian Deposits of the Northwest of the Siberian Platform, Nedra, Leningrad, 1968, p. 242 (in Russian).
[19] V. Astahkin, T. Pegel, Y. Shabanov, S. Sukhov, V. Sundukov, L. Repina, A. Rozanov, A. Zhuravlev, The Cambrian system on the Siberian Platform, in: J. Shergold, A. Rozanov, A. Palmer (Eds.), International Union of Geological Sciences, vol. 27, 1991, p. 134 (in English).
[20] A. Rozanov, L. Repina, M. Apollonov, Cambrian of Siberia, Trans. of Geological and Geophysical In-te 788, Nauka, Novosibirsk, 1992, p. 136 (in Russian).
[21] A. Rozova, Correlation of upper Cambrian sections of South Kazakstan and Siberian Platform, In: Biostratigraphy and Paleontology of Cambrian of Northern Asia, Moscow, 1986, pp. 25–39 (in Russian).
[22] W. Lowrie, Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties, Geophys. Res. Lett. 17 (1990) 159–162.
[23] P. McFadden, M. McElhinny, Classification of the reversal test in palaeomagnetism, Geophys. J. Int. 103 (1990) 725–729.
[24] A. Khramov, Standard nets of paleomagnetic poles for plates of North Eurasia: the connection with the problem of geodynamics of the territory of USSR (in russian), In: Paleomagnetism and Paleogeodynamics of the territory of USSR, VNIGRI, Leningrad, 1991, pp. 154–176.
[25] R. Van der Voo, Paleomagnetism of the Atlantic, Tethys and Iapetus Oceans, Cambridge Univerity Press, Cambridge, 1993, p. 411.
[26] M. Smethurst, A. Khramov, T. Torsvik, The Neoproterozoic and Palaeomagnetic data for the Siberian platform: from Rodinia to Pangea, Earth Sci. Rev. 43 (1998) 1–24.
[27] E.P. Osipova, Paleomagnetic directions and palaeomagnetic poles, in: A. Khramov (Ed.), Reference Book for the USSR, Moscow, 1973, p. 88 (in Russian).
[28] A. Khramov, R. Komissarova, G. Goncharov, in: A. Khramov (Ed.), Paleomagnetism of Paleozoic, Nedra, Leningrad, 1974, p. 236 (in Russian).
[29] S. Odin, Geological time scale, C.R. Acad. Sci. Paris 318 (1994) 59–71.
[30] J. Shergold, Timescales calibration and development 1: Cambrian, Aust. Geol. Surv. Org. Rec. 30 (1995) 1–32.
[31] R. Tucker, W. McKerrow, Early Paleozoic chronology: a review in light of new U–Pb zircon ages from Newfoundland and Britain, Can. J. Earth Sci. 32 (1995) 368–379.
[32] F. Gradstein, J. Ogg, Phanerozoic time scale, Episodes 19 (1996) 3–5.
[33] G. Young, J. Laurie, An Australian Phanerozoic Timescale, Oxford University Press, Melbourne, 1996, p. 279.
[34] J. Meert, A paleomagnetic analysis of Cambrian true polar wander, Earth Planet. Sci. Lett. 168 (1999) 131–144.
[35] J. Jago, P. Haines, Recent radiometric dating of some Cambrian in southern Australia: relevance to the Cambrian time scale, Rev. Espan. Paleont. (1998) 115–122.

[36] E. Landing, S. Bowring, K. Davidek, S. Westrop, G. Geyer, W. Heldmaier, Duration of the Early Cambrian: U–Pb date from Avalonian Wales and the age of the Cambrian–Ordovician boundary, Can. J. Earth Sci. 35 (1998) 303–309.

[37] J. Kirschvink, R. Ripperdam, D. Evans, Evidence for a large-scale reorganization of early Cambrian continental landmasses by inertial interchange true polar wander, Science 277 (1997) 541–545.

[38] J. Shergold, J. Laurie, S. Xiao Wen, Classification and review of the trilobite order Agnostida Salter, 1864: an Australian perspective, Geol. Geophys. Rep. No. 296, Bureau of Mineral Resources, Australia, 1990, pp. 1–93.

[39] S. Bowring, J. Grotzinger, C. Isachsen, A. Knoll, S. Pelechaty, P. Kolosov, Calibrating rates of Early Cambrian evolution, Science 261 (1993) 1293–1298.

[40] W. Compston, I. Willimas, J. Kirschvink, Zichao Zhang, Guogan Ma, Zircon U–Pb ages for the Early Cambrian time-scale, J. Geol. Soc. London 149 (1993) 171–184.

[41] A. Kanygin, T. Moscalenko, A. Yadrenkina, Ordovician System of the Siberian Platform, Nauka, Novosibirsk, 1987 (in English).

[42] R. Ripperdam, J. Kirschvink, Paleomagnetic results from the Cambrian-Ordovician boundary section at Black Mountain, Georgina basin, western Queensland, Australia, in: Webey Laurie (Ed.), Global Perspectives on Ordovician Geology, Balkema, Rotterdam, 1992, pp. 93–103.

[43] R. Ripperdam, M. Margaritz, J. Kirschvink, Carbon isotope and magnetic polarity evidence for non-depositional events within the Cambrian–Ordovician boundary section near Dayangcha Jilin Province, China, Geol. Mag. 130 (1993) 443–452.

[44] E. Eide, T. Torsvik, Paleozoic supercontinental assembly, mantle flushing, and genesis of the Kiaman superchron, Earth Planet. Sci. Lett. 144 (1996) 389–402.